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CALiPER

Application Summary Report 14:

LED Downlight Retrofit Units

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Prepared by:

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1 Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER relies on standardized photometric testing (following the Illuminating Engineering Society of North America [IES] approved method LM-79-08[1]) conducted by accredited, independent laboratories.[2] Results from CALiPER testing are available to the public via detailed reports for each product or through summary reports, which assemble data from several product tests and provide comparative analyses.[3]

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Beginning in 2012, each CALiPER summary report focuses on a single product type or application. Products are selected with the intent of capturing the current state of the market—a cross section ranging from expected low to high performing products with the bulk characterizing the average of the range. The selection does not represent a statistical sample of all available products. To provide further context, CALiPER test results may be compared to data from LED Lighting Facts,[4] ENERGY STAR® performance criteria,[5] technical requirements for the DesignLights™ Consortium Qualified Products List,[6] or other established benchmarks. CALiPER also tries to purchase conventional (i.e., non-SSL) products for comparison, but because the primary focus is SSL, the program can only test a limited number.

It is important for buyers and specifiers to reduce risk by learning how to compare products and by considering every potential SSL purchase carefully. CALiPER test results are a valuable resource, providing photometric data for anonymously purchased products as well as objective analysis and comparative insights. However, LM-79-08 testing alone is not enough to fully characterize a product—quality, reliability, controllability, physical attributes, warranty, compatibility, and many other facets should also be considered carefully.

For more information on the DOE SSL program, please visit http://www.ssl.energy.gov.

[1] IES LM-79-08, *Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*, covers LED-based SSL products with control electronics and heat sinks incorporated. For more information, visit http://www.iesna.org/.
[2] CALiPER only uses independent testing laboratories with LM-79-08 accreditation that includes proficiency testing, such as that available through the National Voluntary Laboratory Accreditation Program (NVLAP).
[3] CALiPER reports are available at http://www.ssl.energy.gov/reports.html. Detailed test reports for individual products can also be obtained from http://www.ssl.energy.gov/search.html.
[4] LED Lighting Facts is a program of the U.S. Department of Energy that showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The DOE LED Lighting Facts program is separate from the Lighting Facts label required by the Federal Trade Commission (FTC). For more information, see http://www.lightingfacts.com.
[5] ENERGY STAR is a federal program promoting energy efficiency. For more information, visit http://www.energystar.gov.
[6] The DesignLights Consortium Qualified Products List is used by member utilities and energy-efficiency programs to screen SSL products for rebate program eligibility. For more information, please visit http://www.designlights.org/.

2 Report Summary

This CALiPER report analyzes the independently tested performance of 11 anonymously purchased LED downlight retrofit units—referred to as the Series 14 products. All the units were tested in a 6-inch insulation contact (IC) rated downlight housing mounted in a 24-inch by 24-inch insulated enclosure. The test results are compared to previous CALiPER tests, ENERGY STAR data, and LED Lighting Facts data for similar products. The differences between in-fixture and standalone testing will be explored in a separate report, which will also analyze the accuracy of manufacturer claims.

The performance of the Series 14 LED retrofit downlight units fit a relatively narrow profile. The products were between 527 and 803 lumens and are roughly comparable to 60 to 100 W incandescent downlights or 13 to 32 W CFL downlights. For most of the Series 14 products, the efficacy was equal to or better than the system efficacy for a typical CFL downlight luminaire, with a range of 39 to 69 lm/W and an average of 49 lm/W. This is substantially better than downlights using incandescent or halogen lamps.

The color quality of the Series 14 products was generally good, with 10 of the 11 products meeting the ENERGY STAR criteria for color rendering index (CRI) and correlated color temperature (CCT). The measured CRIs were not quite as high as some previously tested LED downlight retrofit units, but would generally be acceptable for most applications.

It appears that this product type is settling on a target market of replacing a 65 W incandescent lamp or a less than 32 W CFL lamp in a downlight luminaire; that is, there is a range of performance that has stayed consistent for several years and is suitable for the intended application. One product tested has been on the market for at least three years.

In general, the Series 14 LED downlight retrofit units performed well. They are a viable option for specifiers of residential and light-commercial downlights, especially in retrofit situations. Given the results of the Series 14 tests, most products are best suited for normal ceiling-height applications (8–10 feet). As always, products should be evaluated based on the needs of a specific application. In retrofit applications, consideration should be given to the performance of previously installed products—specifically with regard to the distribution of light and color characteristics—in order to meet user expectations; however, meeting current design criteria should be given priority over matching existing performance.

3 Background

The recessed downlight category encompasses a broad range of luminaires, which share the common attribute of being installed above the ceiling and emitting light through an aperture. The market-wide portfolio of downlights includes products with either round or rectangular apertures ranging from approximately 2-inches to 12-inches in width. Common in both residential and commercial applications, they are primarily used to provide ambient illumination; in some cases, they may also be used for accent illumination. Many manufacturers use a modular system to offer customizable trim and reflector options, providing specifiers with many opportunities to meet design needs. Further, the lumen output and distribution of conventional downlight luminaires is as diverse as the lamps that are installed in them.

Conventional residential and light-commercial downlights—the intended market for LED retrofit downlight units—typically utilize compact fluorescent (CFL), incandescent, or halogen lamps. Depending on the specific application, the source may be either an omnidirectional lamp (e.g., A-lamp, ED-17, triple tube) or a directional lamp, such as a reflector (R, BR, ER) or parabolic aluminized reflector (PAR) lamp. Especially when CFL or other omnidirectional lamps are used, the total luminaire efficacy can be greatly limited by the efficiency of the downlight—a significant portion (50% or more) of the lumens emitted by the lamp can be trapped in the luminaire. Major factors affecting downlight luminaire efficiency include: (1) the finish and/or color of the reflector (also known as the cone)—clear is generally more efficient than colored, and white is more efficient than black in grooved baffles and trims; (2) the optical system used to distribute the light and mitigate glare (e.g., lenses, baffles, or louvers); and (3) the orientation of the lamp, which can be either horizontal, angled, or vertical. With over 800 million downlights installed in the United States—most of which use incandescent lamps—there is potential for substantial energy savings by retrofitting with high-efficacy SSL products.[7]

Several different types of LED products related to downlights are currently available, including replacement lamps, retrofit units,[8] and integral LED luminaires. The boundaries of these categories are sometimes unclear, and the suitability of each depends on many factors, such as the cost, desired performance, visual appeal, or presence of existing infrastructure. The focus of this report is retrofit units; however, in order to provide a comprehensive understanding of retrofit unit performance, it is important to consider their performance relative to the other types of products in the LED downlight arena, as well as to conventional downlights.

LED retrofit units have been available since at least 2007, and are sold by local home improvement stores as well as lighting distributors. They are often selected by homeowners and contractors rather than lighting professionals. Typically, the products are roughly cylindrical and use some type of spring-loaded clip to mount in existing recessed downlight housings. They are most often designed to fit in a 6-inch round aperture, although other options are available. They typically have a medium screw base (also known as Edison or E26) or GU24 base, which is sometimes connected by a whip—a detachable wire connecting the base and the unit—to allow for easier installation. Some products offer the option to be hardwired or to use an adapter to connect to a CFL-type pin base socket (e.g., GX24Q-2).

[7] Navigant Consulting, *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications*. Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy. Washington DC. October 2008.

[8] Although "retrofit unit" is the language used in this report, it is not a standardized term. Here, it refers to LED products that integrate electronic components, trim, and optical systems into a self-contained product while relying on an existing housing for structure. ENERGY STAR uses the term SSL downlight retrofit, which is defined as, "A type of solid state luminaire intended to install into an existing downlight, replacing the existing light source and related electrical components." Notably, a retrofit unit is not the same as a remodel kit, which may have a different configuration, such as using a non-integral driver that is hardwired. Typically, a remodel kit will not use the existing infrastructure, but the pieces can fit through the existing hole in the ceiling.

Although physical attributes may limit their applicability, they also lead to several advantages. Because they are designed to replace the existing trim and reflector,[9] LED downlight retrofit units can encompass a greater volume than LED replacement lamps, which are intended as direct one-for-one replacements for conventional lamps. Thus, they have more surface area for LED packages, as well as space for more sophisticated heat sinks. Improved thermal management capabilities, a larger emitting area, and more room for electronic components mean that retrofit units have the potential for better performance than LED replacement lamps. Additionally, because the entire housing, mounting, and electrical connection may remain in place, retrofit downlight units can be a less expensive option compared to new integral LED downlights, especially when labor costs are considered.

[9] A downlight is comprised of three parts: (1) the housing, which is supports the light source and power supply; (2) the reflector (or cone), which redirects the light from the lamp; and (3) the trim, which provides a finished appearance and may serve as a secondary optical system.

4 Results

This report analyzes the independently tested performance of 11 LED downlight retrofit units—referred to as the Series 14 products—which have a 6-inch aperture, a lumen package of between 500 and 1000 lumens and nominal CCT of 2700 or 3000 K. The products were purchased between June and November 2011. For more on the product selection parameters, both in general and as they pertain to this round, see Appendix A. All the units were tested in a 6-inch insulation contact (IC) rated downlight housing mounted in a 24-inch by 24-inch insulated enclosure (see Figure 1), in accord with the Underwriters Laboratory (UL) *Standard for Safety for Luminaires* (UL1598). In this report, this test method is denoted as "in situ."

Because they are a hybrid of a lamp and a luminaire, it is difficult to establish the most appropriate products to compare to LED downlight retrofit units. Omnidirectional lamps, the type used for many of the benchmark products considered in this report, require a luminaire in order to establish the distribution of light that is applicable to the final installation. The distribution of LED downlight retrofit units is not dependent on the luminaire housing into which it is placed, but the thermal environment of a real installation (i.e., in an insulated ceiling cavity) may change the lumen output. This specific effect has been documented for fluorescent lamps,[10] and it is known that LEDs are sensitive to operating temperature. Generally, in situ testing is most representative of how a product will perform when installed in a building.

The difference between in situ and standalone performance is not only pertinent to this report, but also to installations in architectural spaces. For both new installation and retrofit applications, if in situ performance is substantially different from standalone performance—which is presumably what is being reported by manufacturers—light output, distribution, and color expectations of the user and purchaser may not be met. In addition to this report, a second report on the Series 14 products will examine the difference between standalone and in situ testing, as well as the accuracy of manufacturer claims.

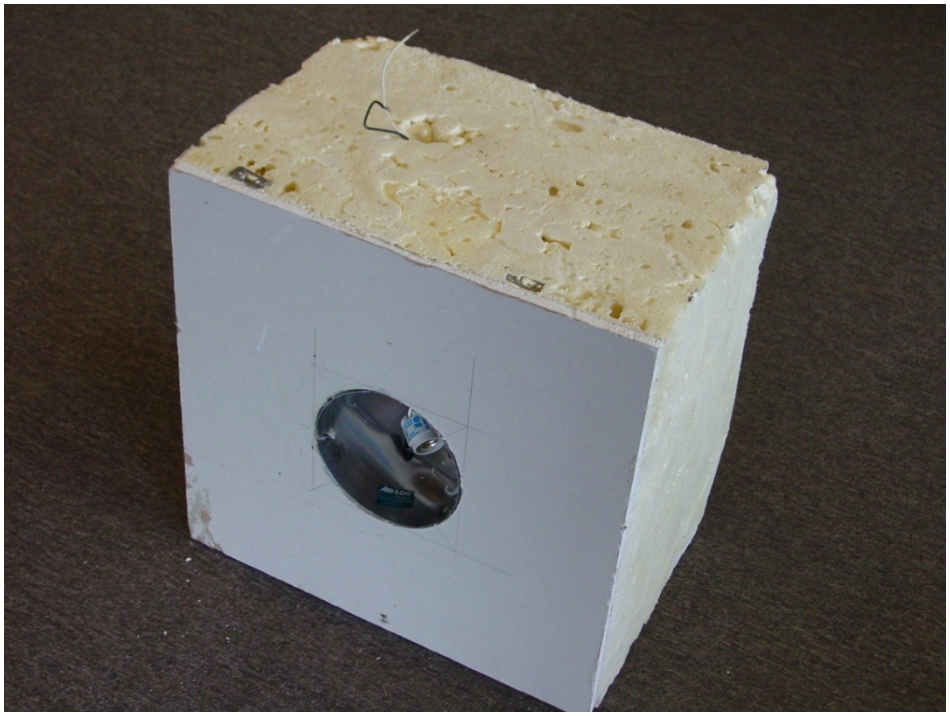


Figure 1.

In situ insulated enclosure. The results described in this report are for tests conducted in situ; that is, during testing the products were installed in a 6-inch insulation contact (IC) rated downlight housing mounted in a 24-inch by 24-inch insulated enclosure, shown here.

[10] Ji, Y. 1995. Thermal Effects in 2'×4' Fluorescent Lighting Systems. Lighting Answers 2(3):1-8.

Figure 2. Photographs of products included in this series of CALiPER testing. Photos are not to scale.

The Series 14 products are shown in Figure 2. General observations and notes regarding this series of products and testing are:

- One product (11-96) is the same model as a product tested in 2008 (08-123). All physical features and written markings appear identical. The difference in measured performance between the two products was within 10% for all metrics considered. Although price is not typically a parameter discussed in CALiPER reports, the 2011 price was 22% lower than the 2008 price.
- Two products (11-74 and 11-97) sold under different labels have identical physical characteristics and the measured performance was within 10% for all metrics considered. They also appear to have been manufactured in the same factory, based on handwritten markings on the product.
- Ten of the eleven products have the common form factor for LED retrofit units; however, one product (11-103) is significantly different, utilizing a much flatter design and appearing to be surface mounted rather than recessed. This product can be installed in either a 5-inch or 6-inch recessed downlight, providing a greater chance of compatibility with existing hardware. It can also be surface mounted to a junction box.
- Although all products are retrofits for luminaires with a 6-inch round aperture, the actual light emitting area for each product varies based on the width of the trim and the type of lens, if any.

CALiPER LED Downlight Data

Series 14 LED Downlight Retrofit Units

The photometric data reported here were collected using a goniophotometer with the product in situ, whereas colorimetric data were collected with the product in open air using an integrating sphere. Table 1 summarizes results for energy performance, distribution, and color characteristics. For definitions of the metrics used in this report, see Appendix B.

Past CALiPER Results for LED Downlights

The CALiPER program has previously tested over 30 products categorized as LED downlights. These data include 8 LED downlight retrofit units purchased between 2007 and 2010, as well as 22 integral LED downlights purchased between 2006 and 2010. A summary of key results for both categories is available in Appendix C; the exact test conditions (e.g., in situ or standalone) are provided with the data. A detailed report for each product is available on the CALiPER website. While some of these products are still on the market (e.g., CALiPER product

Table 1. Results of CALiPER tests for the Series 14 LED downlight retrofit units. Performance criteria include initial output, total power input, luminous efficacy, power factor, center beam candlepower (CBCP), beam angle, color rendering index (CRI), special color rendering index R_9, correlated color temperature (CCT), and D_{uv}. Labels indicate whether the product is listed by ENERGY STAR (ES) or LED Lighting Facts (LF). The data is the average of two samples, unless otherwise noted.

DOE CALiPER Test ID	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	CBCP (cd)	Beam Angle (deg)	CRI	R_9	CCT (K)	D_{uv}[4]	Labels	
11-63	562	14.2	40	0.94	277	96	81	16	3174	0.0029	ES	LF
11-64	689	10.0	69	0.84	459	74	84	11	3046	0.0011		LF
11-73	803	14.0	57	0.92	377	89	78	7	3196	0.0039		LF
11-74[1]	563	13.6	42	0.96	289	93	80	19	3007	-0.0013	ES	LF
11-75	786	14.5	54	0.98	330	100	82	17	3073	-0.0055	ES	LF
11-76	541	13.5	40	0.91	261	88	82	28	3172	-0.0070	ES	
11-82	542	11.0	49	0.87	358	75	84	24	3029	-0.0016	ES	LF
11-96[2,3]	591	13.5	44	0.98	293	93	81	31	3083	0.0027	ES	
11-97[1]	527	13.5	39	0.95	265	93	81	18	2925	0.0032	ES	
11-98	587	11.6	50	0.96	991	36	83	27	3006	-0.0006		
11-103	769	14.0	55	0.80	267	111	80	12	2762	-0.0017		
Minimum	527	10.0	39	0.80	261	36	78	7	2762	-		
Mean	633	13.0	49	0.92	379	86	81	19	3043	-		
Maximum	803	14.5	69	0.98	991	111	84	31	3196	-		

Notes:
1. Products are physically the same, but sold by different companies
2. Product is the same model as CALiPER 08-123. For each metric, the average was within 10% of the value previously measured.
3. Lumen output and efficacy of the two samples tested for Series 14 differed by more than 10%.
4. Listed value is the furthest from zero of the two samples. Red values are outside of the ANSI-defined limits (ANSI C78.377).

08-123/11-96), others were first generation products that performed worse than most products on the market today. Some previously tested products perform very well and are an important supplement in characterizing the range of LED downlight retrofit unit performance. Comparing the Series 14 LED downlight retrofit units to past test data is also useful for historical context.

Supplemental LED Downlight Data

ENERGY STAR

LED downlight retrofit units are considered directional luminaires according to ENERGY STAR documentation. The pertinent performance criteria from the *ENERGY STAR Program Requirements for Luminaires* (version 1.1) are provided in Table 2. Other requirements beyond the scope of LM-79 testing conducted by CALiPER are not included. Using in situ test data—as reported here—to suggest that a product would not meet ENERGY STAR criteria if tested in a different way (e.g., standalone) is generally inappropriate. Nonetheless, comparisons to ENERGY STAR criteria are informative and provide a relative indicator of good product performance. Summary statistics for ENERGY STAR qualified downlights as of February 2012 are provided in Table 3.

LED Lighting Facts Data

As of January 2012, over 500 downlights were listed by LED Lighting Facts. Downlight products are not separated by type (i.e., integral products and retrofit units are listed together), although replacement lamps are classified separately. None of the data listed are known to be from in situ tests. In general, LED Lighting Facts includes a much broader range of products (based on size, shape, and input power) than was considered for this series of downlight testing. Thus, comparisons between the two datasets should be made with care. Summary statistics for downlights listed by LED Lighting Facts as of January 2012 are provided in Table 4.

Conventional Product Benchmarks

CALiPER Testing

CALiPER has tested 12 downlights using conventional lamps. The 12 combinations include three incandescent, one halogen, and eight CFL lamps (including one reflector CFL and one cold cathode CFL), which were installed in several different luminaires. Seven of the tests were performed using the same UL1598 enclosure as was used for the current series of LED product tests. In order to provide an effective comparison, all reported data for conventional products were collected for lamps installed in luminaires, using a goniophotometer. The results of conventional downlight testing are shown in Appendix D.

CALiPER is focused on testing SSL products and is only able to test a limited number of benchmark products.

Table 2. Minimum *ENERGY STAR Program Requirements for Luminaires* (v1.1) criteria relevant to CALiPER testing of LED downlight retrofit units. All Series 14 products were greater than 4.5 inches in diameter and greater than 5 W.

Initial Output (lm)	Efficacy (lm/W)	Power Factor	Distribution	CRI	CCT (K)
375 (≤ 4.5" diameter)	42	0.50 (≤ 5 W)	75% of total initial lumens within the 0–60° zone (axially symmetric about nadir)	80	2700 3000 3500 4000 5000[2]
575 (> 4.5" diameter)		0.70[1] (> 5 W)			

Notes:
1. For residential products only—for commercial products, the minimum is 0.90.
2. For commercial products only—for residential products, the maximum is 4000 K.

Table 3. Summary data for ENERGY STAR-qualified recessed downlights. Includes 815 products listed as of February 2012. Includes both LED downlight retrofit units and integral LED downlights. All data are believed to be from standalone tests.

	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	CRI	CCT (K)
Minimum[1]	346	7.5	34	74	2700
Mean	902	20.4	45	81	3354
Maximum	4,229	107.3	83	95	5000

Notes:
1. Some of the minimum values shown here fall outside current ENERGY STAR criteria; some products were grandfathered in from earlier specifications.

Table 4. Summary data for downlights listed by LED Lighting Facts. Includes 520 products listed as of January 2012. Includes both LED downlight retrofit units and integral LED downlights. All data are believed to be from standalone tests.

	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	CRI	CCT (K)
Minimum	148	4.1	11	62	2658
Mean	1,074	24.1	45	82	3308
Maximum	5,256	107.4	80	95	6500

Especially in this category, CALiPER cannot test enough conventional products to cover the entire scope of the market. Further, some of the products that have been tested are niche products that do not represent the majority of conventional downlights.

Market Scope for Conventional Products

To supplement the CALiPER data, a profile of the conventional product market was established by reviewing manufacturer literature. The boundaries of any specific market segment are often not clearly delineated, but it is nonetheless reasonable to establish a range of performance for *typical* products. There will always be products that exceed normal boundaries.

The conventional downlight market must be characterized by considering system performance, rather than lamp or luminaire performance. For example, lumen output is dependent on both lamp lumens and the efficiency of the luminaire optical system. Typically, conventional luminaires are 40% to 90% efficient, with some dependence on the lamp type used, and output ranges from 200 to 3,000 lumens. For halogen sources, system efficacy will typically be between 4 and 20 lm/W, whereas downlights with CFL lamps will have efficacies between 25 and 50 lm/W.

The color quality of conventional downlights is dependent solely on the installed lamp. A CRI of 80 or higher—near 100 for incandescent or halogen sources—is most common. The most common CCT differs for commercial and residential installations, with 3000 to 4100 K common in commercial applications and 2700 to 3000 K common in residential applications. These are only generalizations, and the specific CCT chosen may be different based on user preference.

5 Analysis

Lumen Output and Efficacy

The range of lumen output for the Series 14 LED downlight retrofit units, 527 to 803 lumens, is comparatively narrow given the wide range of LED downlight products (both retrofit units and integrated downlights) on the market (Figure 3). Considering only omnidirectional lamps installed in a typical recessed downlight, this is approximately equivalent to the output of a downlight with a single 60 to 100 W incandescent or 13 to 32 W CFL lamp. The output of the Series 14 products does not reach the level of a downlight with a single 42 W CFL lamp or higher wattage incandescent lamps, and may not be appropriate in high-ceiling applications.

Notably, some LED downlight retrofit units identified during the selection process had higher lumen output (up to 1500 lumens), but they could not be obtained for this study. Further, some other commercially available LED downlight products have greater lumen packages: one previously tested LED retrofit unit (10-42) and two integral LED luminaires (08-119 and 10-37) exceeded 1,500 lumens. Similarly, many LED downlights listed by LED

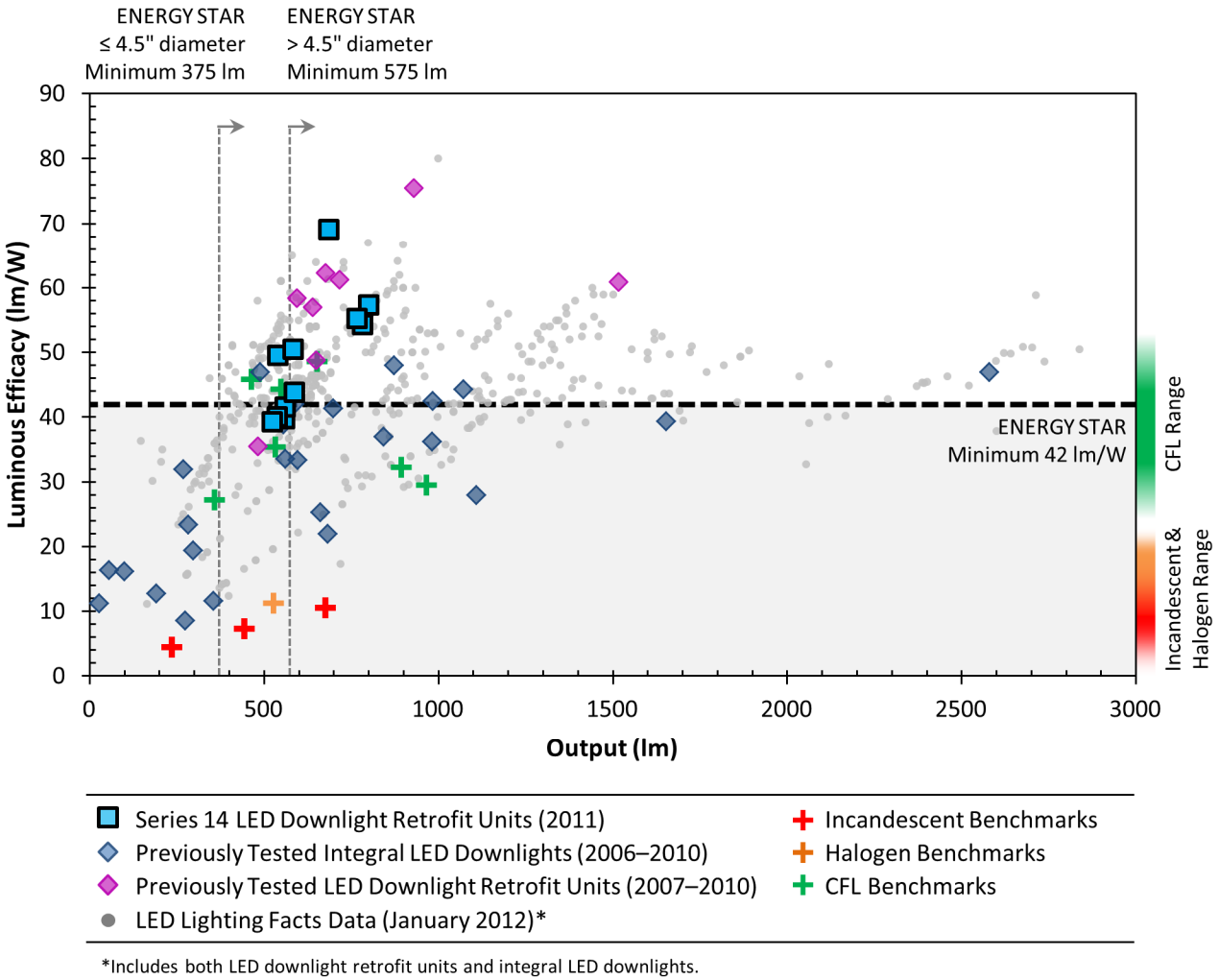


Figure 3. **Efficacy versus lumen output of LED downlights compared to conventional benchmarks.** The Series 14 LED downlight retrofit units form a small grouping compared to the range of all LED downlight products listed by LED Lighting Facts. Several fall just short of meeting ENERGY STAR criteria for lumen output and efficacy. Many previously tested products with very low efficacies were purchased in 2006 or 2007, and in conjunction with the Series 14 products indicate the developing LED downlight market.

Lighting Facts produce over 2,500 lumens; in fact, the average output of the listed products is 1,074 lumens. Thus, it is reasonable to conclude that the broader LED downlight market can cover the typical lumen output range of conventional products (approximately 200 to 3,000 lumens).

Five of the eleven Series 14 LED downlight retrofit units produced fewer than 575 lumens, the minimum output required for ENERGY STAR qualification.[11] However, all five products were between 525 and 575 lumens.[12] Despite not meeting ENERGY STAR criteria, these products still fall in the range of typical low-wattage CFL downlights. Their utility is not necessarily diminished because of the lower lumen output; however, as with all products, they must be used in appropriate applications.

The range in efficacy for the Series 14 products, 39 to 69 lm/W, and the mean efficacy of 50 lm/W are similar to the performance of products listed by LED Lighting Facts or previously tested by CALiPER. Four of the eleven products were less than 42 lm/W, the minimum efficacy required for ENERGY STAR qualification. Compared to the typical luminaire efficacies of CFL downlights—approximately 25 to 50 lm/W—the LED downlight retrofit units perform well and many offer significant energy saving potential.

Distribution of Light

Downlights, especially those considered in this report, are most often used for general ambient illumination rather than focal lighting. Nonetheless, the distribution of light they emit is influential in determining the quantity and placement of luminaires within a space. Several different metrics can be used to describe the distribution of light emitted by a luminaire, including center beam candlepower (CBCP), beam angle, field angle, zonal lumens, and spacing criterion. Each provides a different nuance to communicate the product's performance. ENERGY STAR specifies that downlights—including LED downlight retrofit units—must emit at least 75% of total initial lumens within the 0–60° zone. All the Series 14 products met this criterion. In fact, only one product (11-103) emitted less than 85% of total lumens in the 0–60° zone. It was measured at 77%.

For general ambient lighting, recessed LED downlights should have a beam angle between 60° and 100°.[13] For higher ceiling applications, a narrower beam angle may be suitable; for very low ceilings, a wider beam angle is more likely to produce even lighting across the room. This rule of thumb should be confirmed by a lighting

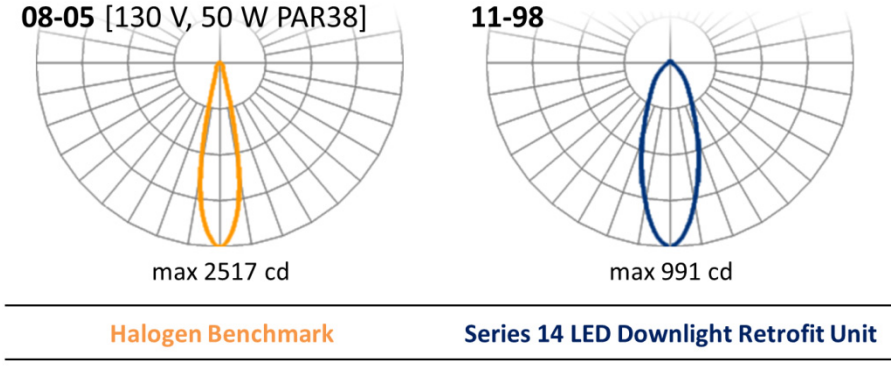


Figure 4.

Polar plots of luminous intensity distribution for a Series 14 LED downlight retrofit unit (narrow distribution) compared to a benchmark conventional product. Note that the scale is different between the two plots. Although product 11-98 is substantially different from others in the series, it is still within the range of what is possible for conventional downlights.

[11] The listed 575-lumen requirement is for downlights with an aperture greater than 4.5 inches. Despite being retrofits for 6-inch recessed downlights, some products have a luminous area that is much smaller than the overall diameter of the product. All the products were classified according to the 6-inch aperture of the downlight they are intended to replace.

[12] Although the results of in situ testing indicate some products failed to meet ENERGY STAR criteria, this does not contradict the qualification of those products. Standalone testing results are likely to be slightly different. Further, only one sample is necessary to achieve qualification and some products may have been grandfathered in.

[13] Downlights may be marketed using terms such as *narrow*, *medium*, or *wide*, rather than a specific number.

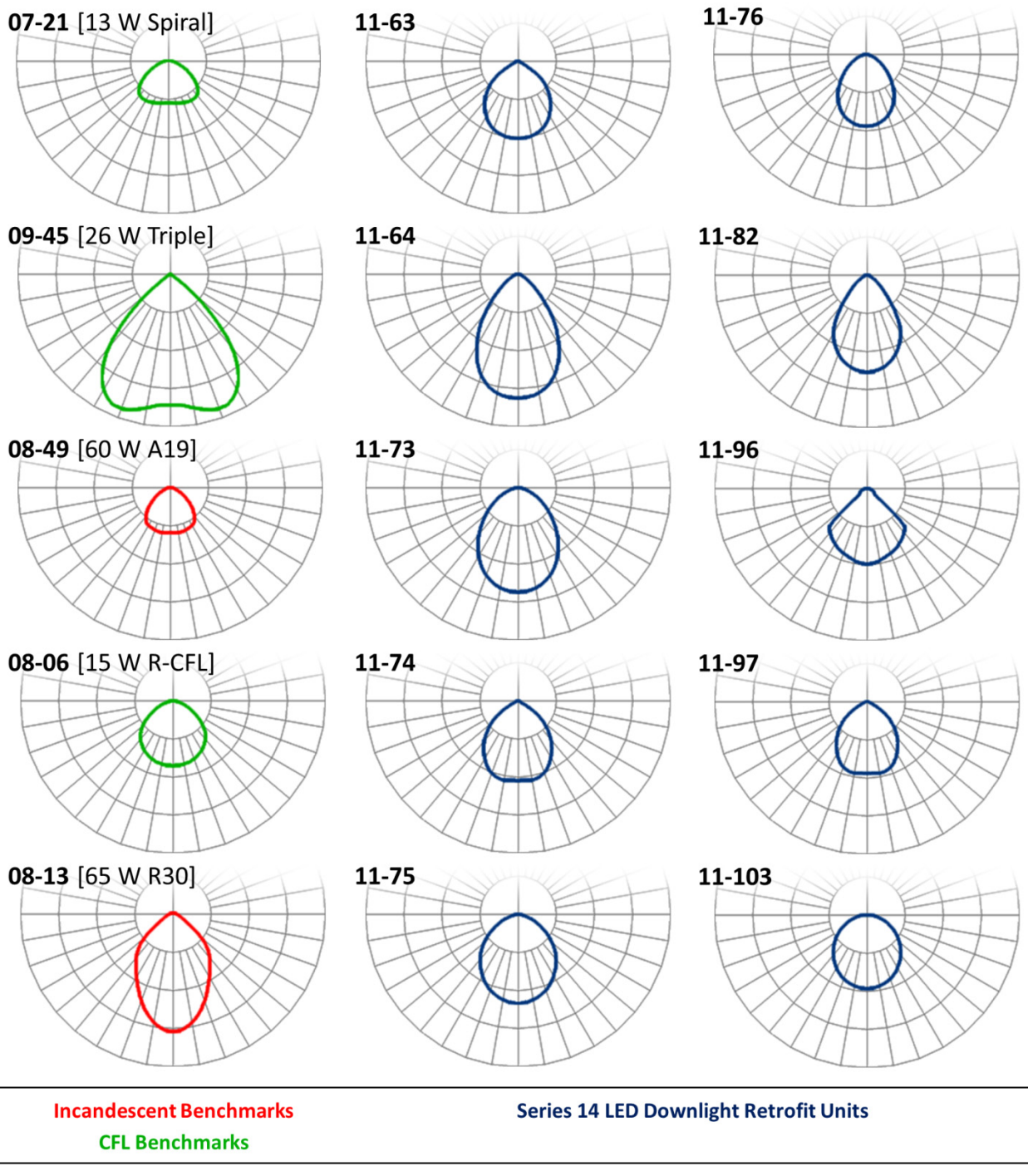


Figure 5. Polar plots of luminous intensity distribution for Series 14 LED downlight retrofit units (medium distribution) compared to benchmark conventional products. All plots have the same maximum value (550 cd). Specific beam angles are listed in Table 1 (LED) or Appendix D (benchmarks). The benchmark products do not capture the entire range of available products, but do show that the LED downlight retrofit units fall within the typical range of conventional downlights.

calculation, based on the specific ceiling height, task surface location, and product spacing. The specific luminous intensity distributions for the Series 14 products are shown in Figures 4 and 5, along with several example conventional products. These plots are useful for comparing the CBCP, as well as the amount of light emitted at high angles, which can cause glare. There was a wide range of measured CBCP values for the Series 14 products,

from as low as 261 cd to as high as 991 cd. There was also a wide range of beam angles, from 36° to 111°, with 9 of 11 products between 74° and 100°. None of the Series 14 products had distributions outside the range of what is possible from a conventional downlight.

For luminaires used for ambient lighting, the direction of maximum intensity is usually straight down, as is the case of most of the downlights shown in Figures 4 and 5. This results in a work plane illuminance that is highest directly below the fixture. Product 09-45, for which the maximum intensity occurs around 20° from nadir, is an exception; this fixture could be spaced farther apart in a room while still producing relatively uniform light levels on the work plane.

Some downlights produce a cosine distribution,[14] which appears as a circle in a polar plot. A downlight with this distribution delivers light evenly to the floor, walls, and other vertical surfaces, such as faces. An approximate example from Series 14 is product 11-103. By contrast, the polar plots for products 08-05 and 11-98 show a narrower distribution, which is better at delivering light to the floor in a tall-ceiling space than a fixture with a cosine distribution. The plots for these two luminaires show that the luminous intensity at nadir (straight down) is 10 times greater than the intensity at 45°.

Glare is another issue related to the distribution of light. Luminaires that emit proportionally less light between 70° and 90°, such as 11-97 and 11-74, may be more visually comfortable for users of the space. However, there are many considerations for selecting luminaires, and there is no substitute for experiencing the luminaire in person.

The distribution of conventional downlights is a function of both the lamp and optics; thus, it is highly customizable and the range of possibilities is not represented well by the small number of CALiPER benchmark products. Downlights using omnidirectional lamps tend to have wide beam angles—they can potentially be shaped by the optics of the luminaire—whereas downlights using directional lamps (e.g., PAR lamps) tend to have narrower distributions that are dependent on the lamp itself. Based on the Series 14 products, there appears to be less variation in the available distributions for LED downlight retrofit units. This could make meeting the needs of a specific application more difficult. If specific distribution characteristics are critical, LED PAR replacement lamps may be a more effective choice than LED retrofit downlight units.

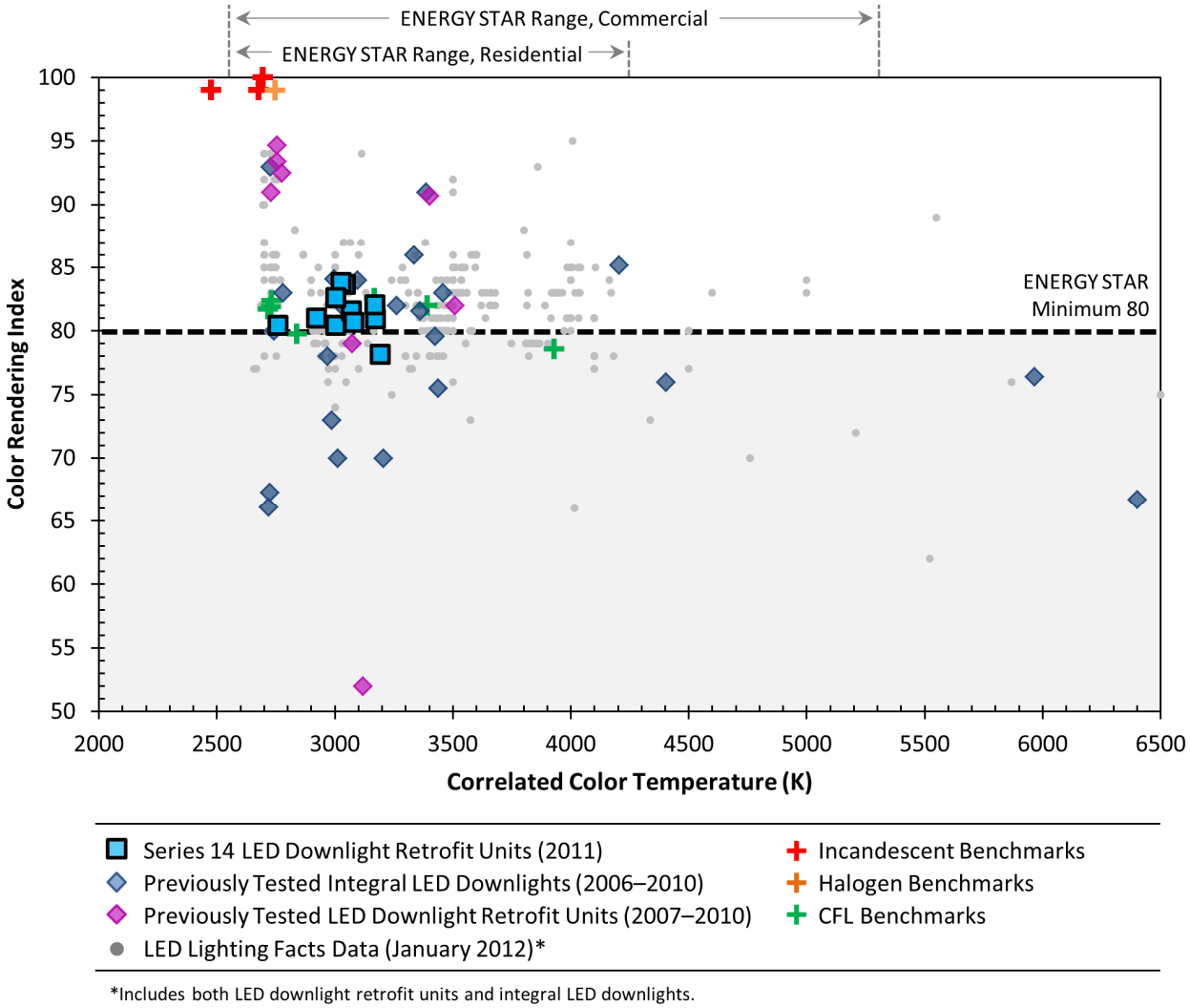
Color Characteristics

The colorimetric performance of the current group of downlight retrofit units falls within a narrow range (see Figure 6). All the Series 14 products have a nominal CCT of either 2700 K or 3000 K CCT—as defined by the American National Standards Institute (ANSI)[15]—and only one product (11-76) did not fall within the ANSI tolerances for white light, as quantified with D_{uv}. Notably, currently available LED downlight retrofit units are available in many different color temperatures, as evidenced by the variety of CCTs for products listed by LED Lighting Facts, although a nominal CCT of 3000 K is most common. Specifiers should be careful to choose a product with a CCT that is appropriate for the application and likely to meet the expectations of the end user.

All the Series 14 products have a CRI between 77 and 84. Only one product (11-73) had a CRI less than 80—it was measured at 78—which is the requirement for ENERGY STAR qualification. All products had an R_9 value

[14] For a cosine distribution, the intensity at a given angle from nadir is equal to the maximum intensity multiplied by the cosine of the angle.

[15] ANSI_NEMA_ANSLG C78.377-2008, *American National Standard for Electric Lamps—Specifications for the Chromaticity of Solid State Lighting Products*, applies only to SSL products used indoors.



*Includes both LED downlight retrofit units and integral LED downlights.

Figure 6. Color rendering index (CRI) versus correlated color temperature (CCT) for the Series 14 LED downlight retrofit units and several sets of comparison data. The performance of the Series 14 products was very consistent, with a CRI just above 80 and a CCT of 3000 K being representative of most products. The other datasets show more variability.

greater than zero.[16] The measured performance is also better than typical CFL lamps (including those listed as benchmarks for this report). Similar to CCT, the range of CRIs for products previously tested by CALiPER or listed by LED Lighting Facts is wide, ranging from approximately 60 to 95. This illustrates the variability in the technology, and means that specifiers should be careful to select a product that is appropriate for the application.

Electrical Characteristics

The input power for the Series 14 products ranged from 10.0 to 14.5 W, with a mean of 13.0 W. This is a fairly narrow range, and contributes to the narrow range in lumen output. LED downlight retrofit units previously tested by CALiPER had a range of 10.2 to 25 W, with a mean of 13.5 W.

[16] Currently, there is no minimum R_9 requirement for luminaires to achieve ENERGY STAR qualification; however, the minimum requirement for integral LED lamps is zero.

The measured power factors ranged from 0.80 to 0.98, with a mean of 0.92. All the products exceeded the ENERGY STAR minimum power factor for residential luminaires (0.70), and 8 of 11 products met the requirement for commercial luminaires (0.90).

Form Factor

Many subtle features related to the form factor of LED downlight retrofit units are not captured by the basic performance metrics. For example, the attachment system used to mount the device in an existing luminaire housing is different from manufacturer to manufacturer, and may or may not work with all installed luminaire housings. Further, the method for attaching to the socket can also vary, with some products using a fixed base and others using a base on a whip. Even the length of the wires used to attach the remote base can affect the ease of installation for the product. These features were not explicitly examined as part of CALiPER testing.

The form factor of LED downlight retrofit units is typically larger and heavier than the equivalent incandescent or CFL trim, which can be problematic in certain housings. The extra mass is necessary for thermal management, which is critical for high performance LED products. As LED technology matures, downlight retrofit units are likely to become smaller and lighter. Although LED technology is better suited for the form factor of retrofit units than replacement lamps—a direct alternative—it is less flexible. Thus, it may be only a transitional product type until LED replacement lamps and modules are fully developed.

Product Labeling

The percentage of LED products available in the consumer market that are either ENERGY STAR-qualified or listed by LED Lighting Facts has shown a steady upward trend. Of the Series 14 products, seven (58%) were ENERGY STAR qualified and six (50%) were listed by LED Lighting Facts. Four products were included in both programs.

6 Conclusions

The performance of the Series 14 LED retrofit downlight units fit a relatively narrow profile. In terms of lumen output, the products were roughly comparable to 60 to 100 W incandescent downlights or 13 to 32 W CFL downlights, and are most suitable for residential and light-commercial applications. For most of the Series 14 products, the efficacy was equal to or better than the system efficacy for a typical CFL downlight luminaire.

The Series 14 products were comparable to LED downlight retrofit units previously tested by CALiPER. It appears that this product type is settling on a target market of replacing a 65 W incandescent lamp or a less than 32 W CFL in a downlight luminaire; that is, there is a range of performance that has stayed consistent for several years and is suitable for the intended application. One product tested has been on the market for at least three years, and the price has decreased by approximately 22%.

The lighting industry would benefit from standardization of terms such as retrofit, remodel, and replacement. Further, product literature should be specific about the housings into which a retrofit product will fit. One "retrofit" LED downlight product was ordered for this study, but the supplied fixture was not designed to be mounted inside an existing downlight housing, but rather to use a supplied housing intended to fit through an existing hole in the ceiling.

In situ testing is important when comparing LED downlight retrofit units to conventional downlight products. However, it makes evaluating manufacturer claims and performance relative to ENERGY STAR criteria more tenuous. A follow-up report will further examine the differences between in situ and standalone performance, and evaluate the accuracy of manufacturer data.

In general, the Series 14 LED downlight retrofit units performed well. They are a viable option for specifiers of residential and light-commercial downlights, especially in retrofit situations. Given the results of the Series 14 tests, most products are best suited for normal ceiling height applications, but products should be evaluated based on the needs of a specific application. In retrofit applications, consideration should be given to the performance of previously installed products—specifically with regard to the distribution of light and color characteristics—in order to meet user expectations; however, meeting current design criteria should be given priority over matching existing performance.

The performance of LED downlight retrofit units is generally similar to LED replacement lamps, although the range of distribution types may be more limited. Integral LED downlights tend to have a greater range of lumen packages, especially at the higher end. Although LED downlight retrofit units were one of the earliest LED product types to compete well with conventional technologies, the future of this form factor is somewhat uncertain given the wide variety of direct alternatives.

Appendix A: Product Selection

Product selection is an important part of the CALiPER process. Products are selected with the intent of capturing the current state of the market—a cross section ranging from expected low to high performing products with the bulk characterizing the middle of the range. However, the selection does not represent a statistical sample of all available products.

Product selection starts with a review of the technology. Beyond relying on professional experience, the team surveys:

- Trade publications, including *Lighting Design + Application*, *LEDs Magazine*, *Mondo ARC*, and *Architectural Lighting*
- Internet websites, including Elumit, DesignLights Consortium, ENERGY STAR, LED Lighting Facts, ESource, and Lightsearch
- National retailers, including Grainger, Goodmart, The Home Depot, Lowe's, Amazon, and Sears
- Other sources, including trade shows (local and national) and manufacturer's representatives

After surveying available products, the CALiPER team characterizes the features of the products and determines what can be standardized to ease comparison. For this report focusing on LED downlight retrofit units, the following features were evaluated and led to the final selection:

- Aperture size – 6-inch is a very common size for residential and commercial downlights, and was the most common size for the products surveyed. Some products were available in other sizes.
- Lumen package – Unlike for other applications, there were fewer options within the individual products for this category. The surveyed products ranged from 550 to 1500 lumens, but some of the high lumen units were not available at the time of ordering.
- Color temperature – A CCT of 2700 to 3000 K is representative of incandescent and halogen sources, and 3000 K CFL lamps are also available. Most of the surveyed LED products fell in this range, but some did not. All selected products had a nominal CCT of 2700 or 3000 K.
- Color rendition – A high CRI was sought, but was not an exclusionary requirement.
- Socket – All the selected products had a medium-base, but some of the products surveyed had other base types or were intended for hard wiring.

Some other non-performance related criteria are also considered:

- Product availability – As a federally funded program, CALiPER focuses on products available in the United States.
- Energy efficiency programs – Some weight is given to including products listed by large energy efficiency programs (e.g., ENERGY STAR). This acts as a quality assurance check and can provide insight into the relative performance of products in these programs.

After establishing a list of appropriate products, attempts are made to purchase the products through standard industry resources (e.g., distributors, retailers). Sometimes, products are not available or cannot be shipped in a timely manner. Thus, the final group of products tested does not always match the original selection process list.

Appendix B: Definitions

Beam Angle Degrees (°)	The angle between the two directions for which the intensity is 50% of the maximum intensity (ANSI/IES RP-16-10) or center beam intensity (ANSI C78.379-2006), as measured in a plane through the beam axis. For example, if the maximum intensity is 1000 cd, the angle at which the intensity is 500 cd is half of the beam angle. If 500 cd occurs at 20° from center beam, then the beam angle is 40°.
Center Beam Candlepower (CBCP) Candela (cd)	The luminous intensity at the central axis of the beam, which typically corresponds to a vertical angle of 0° (called nadir for lamps oriented downward). Although candlepower is a deprecated term, it is still widely used in this context.
Correlated Color Temperature (CCT) Kelvin (K)	The absolute temperature of a blackbody radiator having a chromaticity that most nearly resembles that of the light source. CCT is used to describe the color appearance of the emitted light.
Color Rendering Index (CRI or R_a)	A measure of color fidelity that characterizes the general similarity in color appearance of objects under a given source relative to a reference source of the same CCT. The maximum possible value is 100, with higher scores indicating less difference in chromaticity for a sample of eight color samples illuminated with the test and reference source.
D_{uv}	The distance from the Planckian locus on the CIE 1960 UCS chromaticity diagram (also known as u', 2/3 v'). A positive value indicates the measured chromaticity is above the locus (appearing slightly green) and a negative value indicates the measured chromaticity is below the locus (appearing slightly pinkish). The American National Standards Institute provides limits for D_{uv} for nominally white light.
Luminous Efficacy Lumens per watt (lm/W)	The quotient of the total luminous flux emitted and the total input power.
Field Angle Degrees (°)	The angle between the two directions for which the intensity is 10% of the maximum intensity (ANSI/IES RP-16-10) or center beam intensity (ANSI C78.379-2006), as measured in a plane through the beam axis. For example, if the CBCP is 1000 cd, the angle at which the intensity is 100 cd is half of the field angle. If 100 cd occurs at 32° from center beam, then the field angle is 64°.
Input Power Watts (W)	The power required to operate a device (e.g., a lamp or a luminaire), including any auxiliary electronic components (e.g., ballast or driver).
Luminous Intensity Distribution Candela (cd)	The directionality of radiant energy emitted by a source, which may be shown using one of several techniques. It is most often presented as a polar plot of the candelas emitted in a vertical plane through the center of the lamp or luminaire.
Output Lumens (lm)	The amount of light emitted by a lamp or luminaire. The radiant energy is weighted with the photopic luminous efficiency function, V(λ).
Power Factor	The quotient of real power (watts) flowing to the load (e.g., lamp or fixture) and the apparent power (volt amps) in the circuit. Power factor is expressed as a number between 0 and 1, with higher values being more desirable.

Special Color Rendering Index R_9	A measure of color fidelity that characterizes the similarity in color appearance of deep red objects under a given source relative to a reference source of the same CCT. The maximum possible value is 100, with higher scores indicating less difference in chromaticity for the color sample illuminated with the test and reference source. R_9 and R_a (CRI) are part of the same CIE Test-Color Method, but the R_9 color sample is not included in calculation of R_a.
Spacing Criterion (SC)	The estimated ratio between the mounting height above the work plane and luminaire spacing necessary for a regular array of a given luminaire to produce a work plane illuminance that is acceptably uniform. For example, for a luminaire recessed into a 10-foot ceiling with a work plane that is 30 inches above the floor, if the spacing criterion is 1.4, the luminaire should be spaced no more than 10.5 feet on center (1.4 × (10 – 2.5) = 10.5). Spacing criterion is also referred to the spacing-to-mounting-height ratio (S/MH).
Zonal Lumens	The amount or proportion of lumens emitted in different vertical or horizontal regions related to a lamp or luminaire. Typically, it is expressed in vertical increments from nadir, but could be also expressed in horizontal zones [e.g., the IES Luminaire Classification System, which also defines backlight, uplight, glare (BUG) ratings].

Appendix C: Previous CALiPER Testing of LED Downlights

Table C1. Summary data for previous CALiPER tests of LED downlight retrofit units. All photometric tests were conducted in the standalone configuration using a goniophotometer, unless otherwise noted. All colorimetric data were measured using an integrating sphere, with the product in the standalone configuration. The first two digits of the CALiPER test ID indicate the year in which the product was purchased.

DOE CALiPER Test ID	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	CBCP (cd)	Beam Angle (deg)	CRI	R_9	CCT (K)	D_{uv}	Labels	
07-31	716	11.7	61	0.97	279	106	95	76	2754	0.0005	ES	
07-31D[1]	639	11.2	57	0.97	251	105	93	77	2753	0.0005	ES	
07-47	676	10.8	62	0.97	266	105	91	61	3402	-0.0008		
08-118	482	13.4	36	0.84	151	126	52	-5	3119	-0.0020		
08-123	649	13.3	49	0.98	311	94	79	26	3073	0.0040	ES	
10-38	594	10.2	58	0.87	322	83	93	94	2776	-0.0004	ES	LF
10-41	929	12.3	76	0.97	536	76	91	91	2729	-0.0010		LF
10-42[1]	1,531	25.0	61	0.98	740	94	82	35	3509	-0.0010	ES	
Minimum	482	10.2	36	0.84	151	76	52	-5	2729	-		
Mean	777	13.5	57	0.94	357	99	84	57	3014	-		
Maximum	1,531	25.0	76	0.98	740	126	95	94	3509	-		

Notes:
1. In situ test.

Table C2. Summary data for previous CALiPER tests of integral LED downlights. All data are for products tested in the standalone configuration using an integrating sphere, except for CBCP and beam angles, which were measured using a goniophotometer. The first two digits of the CALiPER test ID indicate the year in which the product was purchased.

DOE CALiPER Test ID	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	CBCP (cd)	Beam Angle (deg)	CRI	R_9	CCT (K)	D_{uv}[1]	Labels
06-01	193	15.1	13	0.77	88	94	70	-	3012	-	
06-03	298	15.4	19	0.78	-	-	67	-	2724	-	
07-04	357	31.0	12	1.00	428	56	76	-	5964	-	
07-05	662	26.2	25	0.99	686	66	76	-	4402	-	
07-42	101	6.3	16	0.75	52	94	66	-	2719	-	
07-61	29	2.5	11	0.85	165	25	67	-	6401	-	
08-77	985	23.2	43	0.99	985	66	85	-	4203	-	
08-119	1,654	42.0	39	0.99	834	81	82	-	3262	-	
08-124	275	32.1	9	0.98	287	61	70	-	3204	-	
09-24	589	14.0	42	0.97	297	85	73	-	2987	-	ES
09-44	490	10.0	47	0.96	460	55	93	-	2727	-	ES
09-61	269	8.0	32	0.59	778	29	83	-	2779	-	
09-69	1,110	39.0	28	1.00	658	86	91	-	3385	-	
09-70	683	30.0	22	0.99	833	42	86	-	3334	-	
09-75	843	23.0	37	0.99	377	98	83	-	3456	-	
10-46	57	3.5	16	0.86	246	23	80	-	2742	0.0020	
10-47	597	17.9	33	0.76	2,525	26	84	-	3095	0.0000	
10-48	562	16.7	34	0.99	561	57	82	-	3361	0.0001	
10-49	874	18.2	48	0.98	963	62	78	-	2967	0.0020	
10-50	699	16.9	41	0.98	430	71	82	-	3028	-0.0019	
10-37	2,580	54.9	47	1.00	4,493	44	80	-	3424	-0.0022	ES
10-52	983	27.1	36	0.98	1,388	49	76	-	3436	0.0085	
10-53	1,072	24.2	44	0.98	796	72	84	-	2995	0.0020	
Minimum	29	2.5	9	0.59	52	23	66	-	2967	-	
Mean	694	21.6	30	0.92	833	61	79	-	3202	-	
Maximum	2,580	54.9	48	1.00	4,493	98	93	-	3436	-	

Notes:

1. Red values are outside ANSI-defined limits (ANSI C78.377).

Appendix D: CALiPER Testing of Conventional Products

Table D1. Summary data for CALiPER tests of conventional downlights. All photometric tests were conducted in situ (lamp in a luminaire) using a goniophotometer. Colorimetric data were measured using an integrating sphere, using only the bare lamp. Some products included here were not tested in an IC-rated fixture, but still provide a reasonable basis for comparison. The first two digits of the CALiPER test ID indicate the year in which the product was purchased.

DOE CALiPER Test ID	Source Type	Luminaire Type	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	CBCP (cd)	Beam Angle (deg)	CRI	CCT (K)
08-13 (A)	Inc. R30	6" round, IC	678	64.8	11	1.00	431	77	99	2677
08-49 (B)	Inc. A19	6" round, IC	446	61.1	7	1.00	166	105	100	2696
08-04 (A)	Inc. A19	6" round, IC	238	53.9	4	1.00	80	103	99	2476
08-05 (B)	Hal. PAR38[1]	6" round, IC	529	46.7	11	1.00	2,517	22	99	2746
07-15	CFL	5" round	359	13.2	27	0.99	210	83	79	3928
07-21	CFL	6" round	550	12.4	44	0.95	168	120	82	2729
08-06 (B)	RCFL	6" round, IC	653	13.5	49	0.52	236	110	82	2730
08-18 (A)	CCFL	6" round, IC	534	15.1	35	0.86	187	106	80	2839
08-27 (A)	CFL	6" round, IC	466	10.2	46	0.54	97	121	82	2717
09-45	CFL	6" round	896	27.8	32	1.00	473	87	83	3166
09-66	CFL	6" round	967	32.8	30	1.00	971	60	82	3392
Minimum			238	10.2	4	0.52	80	22	79	2476
Mean			574	31.9	27	0.90	503	90	88	2918
Maximum			967	64.8	49	1.00	2,517	121	100	3928

Notes:
1. 130 V product.

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